An Issue of Boundary Value for Velocity and Training Overhead Using Cooperative MIMO Technique in Wireless Sensor Network

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Abstract. *A boundary value of velocity of data gathering node (DGN) and a critical value for training overhead beyond which the cooperative communication in wireless sensor network will not be feasible is proposed in this paper. Multiple Input Multiple Outputs (MIMO) cooperative communication is taken as an application. The performance in terms of energy efficiency and delay for a combination of two transmitting and two receiving antennas is analyzed. The results show that a set of critical value of velocity and training overhead pair is present for the long haul communication from the sensors to the data gathering node. Later a graphical relation between boundary value of training overhead and velocity is simulated. A mathematical relation between velocity and training overhead is also developed. The effects of several parameters on training overhead and velocity are analyzed.*

Keywords

Cooperative technique, data gathering node, training overhead, velocity, wireless sensor networks.

1. Introduction

Cooperative technique nowadays is a burning issue for energy minimization in remotely clustered Wireless Sensor Networks. Recent hardware advancements allow more signal processing functionality to be integrated into a single chip. RF transceiver, A/D and D/A converters, baseband processors, and other application interfaces are integrated into a single device to be used as a fully-functional wireless node. SOC (System on Chip) and NOC (Network on Chip) are being developed for integrated system design. These SOC or NOC based wireless nodes typically operate with small batteries for which replacement, when possible, is very difficult and expensive. Thus, in many scenarios, the wireless nodes must operate without battery replacement for many years. Consequently, minimizing the energy consumption is a very important design consideration.

MIMO techniques which require complex transceiver circuitry and signal processing leading to large power consumptions at the circuit level, has precluded the application of MIMO techniques to energy limited wireless sensor networks. Moreover, physical implementation of multiple antennas at a small node may not be feasible. As solutions to the latter problem cooperative MIMO and virtual antenna array concepts have been proposed to achieve MIMO capability in a network of single antenna. In traditional wireless systems the main power consumption is due to the actual transmissions power. However, this may not be the case in a wireless sensor network. In fact, in some cases it is the circuit energy needed for receiver and transmitter processing that is dominant. Thus, usual energy optimization techniques that minimize the required transmission energy may not be effective in wireless sensor networks.

Motivated by information theoretic predictions on large spectral efficiency of multiple-input-multiple-output (MIMO) systems, there has been a great amount of research on various MIMO techniques for wireless communication systems [1], [2]. Cooperative MIMO [5] and virtual antenna array [1] concepts have been proposed to achieve MIMO capability in a network of single antenna (single-input/single-output or SISO) nodes. Energy efficiency and delay analysis has been done to explain that the cooperative MIMO outperforms the SISO after a certain distances [5], [6], [7]. But the use of all the sensors in a cluster makes the cooperative transmission inefficient. Recently researches have been done to optimize the cooperative transmission by using single parameter selection of cooperative nodes [2], [19], [20], [22]. A closer look at the selective approach in total energy and delay comparisons between selective and nonselective cooperative MIMO communications was taken in [2]. It is further analyzed in [19] showing channel estimation energy variation. Inter sensor distance impact is also shown in this paper. The results showed that the selective approach outperforms the nonselective approach and in fact leads to better energy optimization and smaller end-to-end delay. But all these single parameter node selection algorithms are incomplete in a sense that they are not considering all the selection parameters which contribute to minimize energy consump tion. Selective approach is analyzed in [3] using a selection function which is a combination of channel condition, residual energy, intersensor distance in a cluster and geographical location of the sensors. Based on correlation of the data, two separate schemes are considered here. In both the schemes, selective approach outperforms the nonselective and single parameter selective approach. Motivated by the results of some recent papers we concentrated our work on the cooperative MIMO approach but our special interest in this particular paper is to analyze the velocity of the sensor nodes and the training bits used for channel estimation.

In this work, we propose to find the boundary value of the velocity of Data Gathering Node (DGN) for a MIMO based cooperative communication for energy-limited wireless sensor networks. We also propose a critical value for training overhead beyond which the scheme will not be feasible. We will analyze the performance in terms of the total energy consumption for cooperative MIMO and SISO cases. And then we develop a relation between the boundary value of velocity and the boundary value of training overhead who are found to be inversely related.

This paper is organized as follows: In section 2, we present the system model. Section 2 is divided into three subsections. Firstly we describe the system, then we concentrate on the energy model and finally we explain the cooperative technique on which we experiment our work. We closely follow the model developed in [1], [2], [3], [5], [6], [19], [20], and [21] but for simplicity we consider non selective cooperative MIMO. In section 3 we investigate the estimation of boundary value of velocity and training overhead and section 4 concludes the paper.

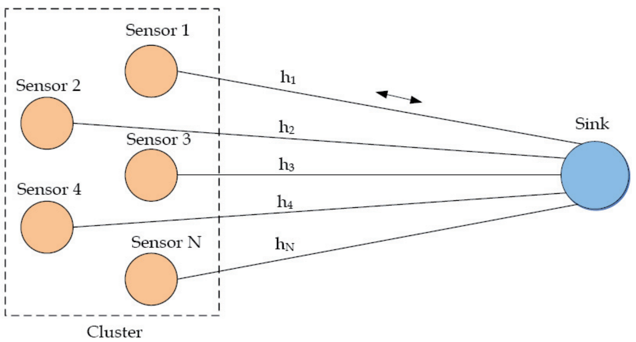

Fig. 1. System model.

2. System Model

In this section, the system will be described at first. Then the energy model will be developed. Finally the cooperative communication model will be discussed.

2.1 System Description

The system considered in this analysis is a clustered Wireless Sensor Network (WSN) shown in Fig. 1. We consider a narrow-band, flat fading, communication link connecting two wireless sensor nodes, which can in general be MIMO, multiple-input-single-output (MISO), single-input multiple-output (SIMO) or single-input-single-output (SISO). As assumed in [1], we will omit the energy consumption in baseband signal processing blocks and will assume uncoded communication in order to keep the analysis simple.

The transmitter and receiver are equipped with N_T and N_R antennas, respectively. In the transmitter side, N_T antennas are distributed in N_T number of sensors and are used as multiple inputs in a cooperative way. In the receiving side, N_R antennas are placed at DGN. For simplicity, we are not using the system with selective cooperative transmission. We only concentrate our work on the general cooperative communication where all the nodes are used in a cooperative way.

2.2 Energy Model

The total power consumption can be categorized into two main parts, namely, the power consumption of all the power amplifiers P_{PA} which is function of the transmission power P_{out}, and the power consumption of all other circuit blocks P_C .

$$P_T = P_{PA} + P_C \tag{1}$$

where P_{PA} is the amplifier power and P_C is the circuit power. The amplifier power can be calculated using the following equation

$$P_{PA} = P_{out} + \alpha P_{out} \, . \tag{2}$$

Here $\alpha = \xi/\eta$-1 where η is the drain efficiency and ξ is the peak to average ratio. We will do our analysis based on uncoded MQAM. For MQAM, $\xi = 3\left(\sqrt{M}-1\right)/\left(\sqrt{M}+1\right)$ and the number of bits per symbol (constellation size) defined as $b = \log_2 M$.

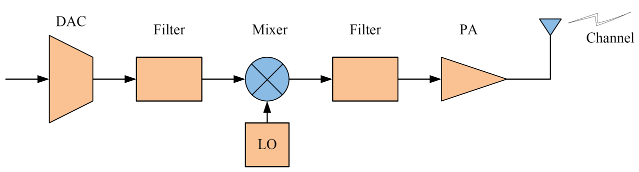

Fig. 2. Transmitter circuit block.

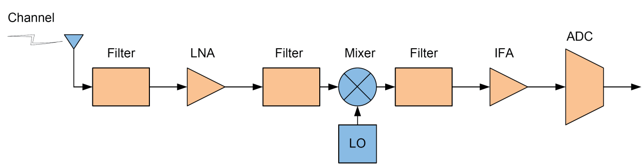

Fig. 3. Receiver circuit block.

When the channel only experience a k^{th} -power path loss with Additive White Gaussian Noise (AWGN), P_{out} can be calculated according to the link budget relationship as follows.

$$P_{out} = \bar{E}_b R_b \times \frac{16\pi^2 d^k}{G_t G_r \lambda^2} M_l N_f \tag{3}$$

where $\bar{E}_b$ is the average energy per bit required for a given bit error rate (BER) specification, R_b is the transmission bit rate, d is the transmission distance, G_t and G_r are the transmitter and receiver antenna gains respectively, λ is the carrier wavelength, M_l is the link margin compensating the hardware process variations and other background noise, N_f is the receiver noise figure defined as $N_f = N_r/N_0$ where N_r is the Power Spectral Density (PSD) of the total effective noise at the receiver input and N_0 is the single-sided thermal noise PSD at the room temperature.

The second term in the total power consumption is the circuit power which consists of both the transmitter and the receiver circuit blocks which is shown in Fig. 2 and Fig. 3. The power consumption in these blocks are divided into several sub blocks

$$\begin{aligned} P_{ct} &= P_{mix} + P_{syn} + P_{filt} + P_{DAC} \,, \\ P_{cr} &= P_{mix} + P_{syn} + P_{LNA} + P_{filr} + P_{IFA} + P_{ADC} \end{aligned} \tag{4}$$

where P_{ct} and P_{cr} are circuit powers for the transmitter and the receiver respectively. P_{mix}, P_{syn}, P_{filt}, P_{filr}, P_{LNA}, P_{IFA}, P_{DAC} and P_{ADC} are the power consumption values of the mixer, the frequency synthesizer, the active filters at the transmitter and at the receiver side, the low noise amplifier, the intermediate frequency amplifier, the D/A and the A/D converter, respectively. The total energy consumption per bit can be written as

$$E_{bt} = (P_{PA} + P_C)/R_b \tag{5}$$

where R_b is the actual bit rate and can be replaced by $R_b^{eff} = R_b(F - pN_T)/F$ when pN_T training symbols are inserted in each block to estimate the channel. The block size is equal to F symbols and can be obtained by setting F = floor of $T_C R_S$ where R_S is the symbol rate and T_C the fading coherence time. The fading coherence time can be estimated as $T_C = 3/(4 f_m \sqrt{\pi})$ where the maximum Doppler shift f_m is given by $f_m = v/\lambda$ with v being the velocity and λ being the carrier wavelength. The total energy consumption is estimated by multiplying E_{bt} by the number of bits L_i to be transmitted. For getting the value of $\bar{E}_b$, we use the numerical search using the equation shown in simulation results section.

2.3 Cooperative Communication

For sensor networks, maximizing the network lifetime is the main concern. Since sensor networks are mainly designed to cooperate on some joint task where per-node fairness is not emphasized, the design intention is to minimize the total energy consumption in the network instead of minimizing energy consumption of individual nodes. To minimize the total energy consumption of multiple nodes from a network perspective, cooperative MIMO was proposed in many papers.

In a typical sensor network, information collected by multiple local sensors need to be transmitted to a remote central processor. If the remote processor is far away, the information will first be transmitted to a relay node, then multi hop-based routing will be used to forward the data to its final destination. As we know that MIMO (including MISO, SIMO, and MIMO) can provide energy savings in the fading channels, we can allow cooperative transmission among multiple sensor nodes and treat them as multiple antennas to the destination node. Cluster head acts as the coordinator for cooperative transmission in this cluster based WSN. Data aggregation is necessary in a cooperative MIMO communication when the sensed data are partially or fully correlated. Data aggregation reduces the data size but increases the steps in cooperative MIMO communication. The issue is explained in many research papers [3], [19], [20]. For simplicity, we are excluding the data aggregation in our cooperative MIMO model and hence consider that the sensed data are uncorrelated.

Energy consumption of the cooperative MIMO based scheme consists of two terms: the energy required for local communication among data collection sensors and the energy required for long-haul communications from data collection nodes to the data gathering node. We assume that there are N_T numbers of data collection sensors and the data gathering node is equipped with N_R number of receiver antenna elements. The average energy per bit per sensor node for local communications is denoted by E_i^l and the average energy per bit for the global or long-haul communication is denoted by E^g. If we assume that each sensor node has L_i number of bits to transmit to the data gathering node then the total energy required in order to communicate the data from all nodes to the data gathering node is given by [1].

$$E^{MIMO} = \sum_{i=1}^{N_T} L_i E_i^l + E^g \sum_{i=1}^{N_T} L_i \,. \tag{6}$$

We assume that the maximum separation between two data collection sensors is d_m meters and we assume that the global communication distance $d >> d_m$. We also assume that this global distance is the same for each pair of data collection nodes and the data gathering node. As the DGN is not energy constrained, we exclude the energy calculations at the data gathering node side.

In contrast to this cooperative MIMO-based scheme, the total energy required in communicating the same amount of data by a traditional wireless sensor network based on SISO techniques will be

$$E^{SISO} = \sum_{i=1}^{N_T} L_i E_i^{SISO} \tag{7}$$

where the average energy per bit E_i^{SISO} for the transmission from sensor node i to data gathering node and can be obtained as a special case of the global distance communications with $N_T = N_R = 1$.

3. Boundary Value of Velocity and Training Overhead

Boundary value of velocity and training overhead are the values beyond which the successful cooperative transmission is not possible. We can find these boundary values using any of these analytical or simulation approaches. We start with the simulation approach.

3.1 Simulation Approach:

In this approach, we will first simulate the cooperative MIMO and see the impact of velocity and training overhead. From the simulation results, we will find the boundary values of these parameters beyond which successful transmission is not possible. In order to get the total communication energy consumption, the average energy per bit required for a given BER, $\overline{E}_b$ needs to be determined. The average BER of a MIMO system using Alamouti schemes with MQAM is given by [15]

$$\overline{P_b} \approx E_H\left[\frac{4}{b}\left(1-\frac{1}{2^{\frac{b}{2}}}\right)Q\left(\sqrt{\frac{3b}{M-1}\gamma_b}\right)\right] \quad \text{for} \quad b \geq 2, \tag{8}$$
$$\approx E_H\left[Q\left(\sqrt{2\gamma_b}\right)\right] \quad \text{for} \quad b=1$$

where E_H denotes the expectation with variable H, and Q is defined as $Q(x)=1/\sqrt{2\pi}\int_x^{\infty} e^{-t^2/2}dt.$

f_c = 2.5 GHz	η = 0.35
G_tG_r = 5 dBi	N_0 = – 171 dBm/Hz
B = 10 kHz	k = 2 for local communication
N_f = 10 dB	k = 3 for long haul comm.
M_l = 40 dB	P_{mix} = 30.3 mW
P_{syn} = 50.0 mW	$P_{filt} = P_{filr}$ = 2.5 mW
P_{LNA} = 20 mW	L_i = 10 kb

Tab. 1. System parameters.

In our approach we get the value of $\overline{E}_b$ by using numerical search. We have taken ten thousand randomly generated channel samples and averaged to find the desired bit error rate at each transmission distance. For simplicity, we concentrate on an M-ary QAM, 2×2 MIMO system based on the Alamouti scheme. For b = 2, the bit error rate of an M-ary QAM MIMO system ($M = 2^b$) with a square constellation (i.e. b is even) in Rayleigh fading is given by

$$P_b = \frac{4}{b}\left(1-\frac{1}{2^{b/2}}\right)\frac{1}{2^{N_TN_R}}\left(1-\frac{1}{\sqrt{1+\frac{1}{\overline{E}_b/2N_0}}}\right)^{N_TN_R} \tag{9}$$
$$\times\sum_{k=0}^{N_TN_R-1}\frac{1}{2^k}\binom{N_TN_R-1+k}{k}\left(1+\frac{1}{\sqrt{1+\frac{1}{\overline{E}_b/2N_0}}}\right)^{k}$$

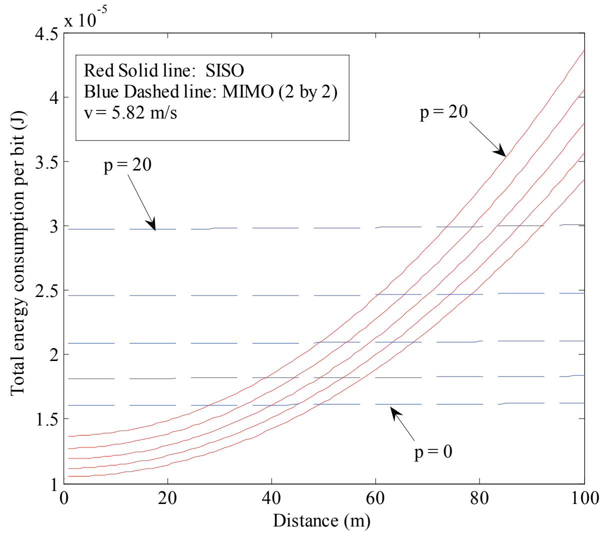

Fig. 4. Total energy consumption per bit over distance for variable p (training overhead).

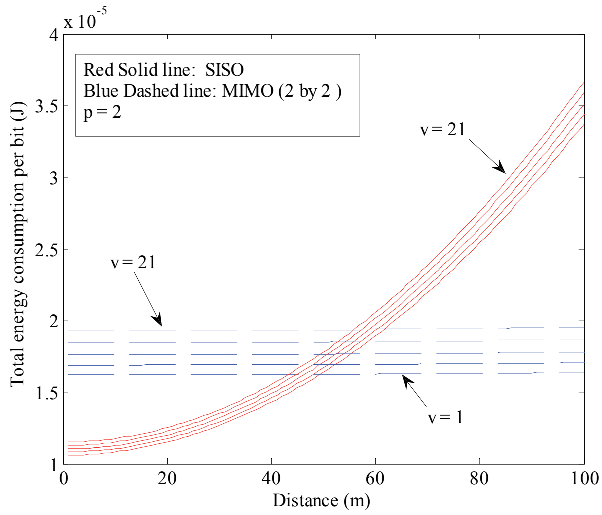

Fig. 5. Total energy consumption per bit over distance for variable v (velocity).

In the case of local communication, the distance d_m between the sensors within a cluster is chosen 1 m to avoid complexity. It is assumed that the long haul distance is same from the sensors within a cluster. For the long haul communication, SISO can be a special case of MIMO system. The system parameters used in simulation are shown in Tab. 1.

For simulation we consider that all the sensors in a cluster are transmitting the same data size L_i = 10 kb. We experimented on a 2 by 2 MIMO system and generated the curve of total energy consumption per bit for both the cooperative MIMO and SISO cases. We observe that cooperative MIMO outperforms SISO as in the other papers.

Then we vary the training overhead keeping the velocity fixed. Fig. 4 shows the variation for this experiment. When p increases, the total energy consumption increases and cooperative MIMO outperforms SISO after a larger distance. Again we vary the velocity keeping the training overhead fixed. It is shown in Fig. 5. When v increases, the total energy consumption increases and cooperative MIMO outperforms SISO after a larger distance. When the velocity remains constant, the block size F becomes constant for a particular carrier frequency through the maximum Doppler shift f_m. So, the boundary value of p depends on the term $F - pN_T$ and the boundary condition is $p \le F/N_T$. For velocity $v = 5.82$ m/s, the block size F becomes 87 and Fig. 6 shows that for $p = 50$ and $N_T = 2$, the total energy consumption becomes infeasible as the value of p doesn't satisfy the boundary condition. The same is true for making the training overhead fixed and varying the velocity v. It is shown in Fig. 7. Tab. 2 shows a sample of the boundary value pairs of p and v. If we keep one fixed then the value of others becomes its boundary value.

Boundary value of p	Boundary value of v (m/s)
10	24
15	16
20	12
25	09

Tab. 2. Boundary value for velocity v and training overhead p.

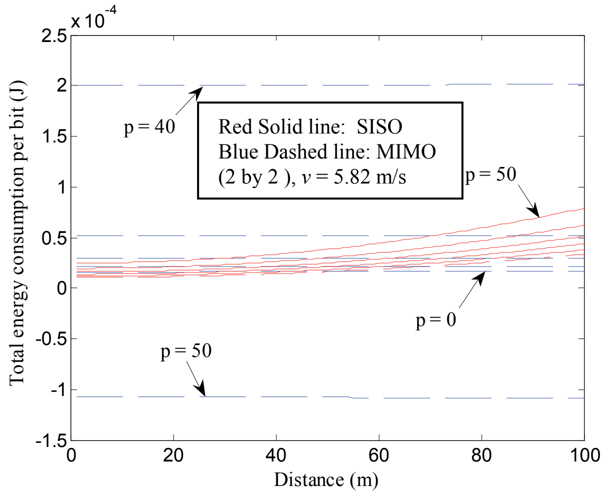

Fig. 6. Total energy consumption per bit over distance for variable p.

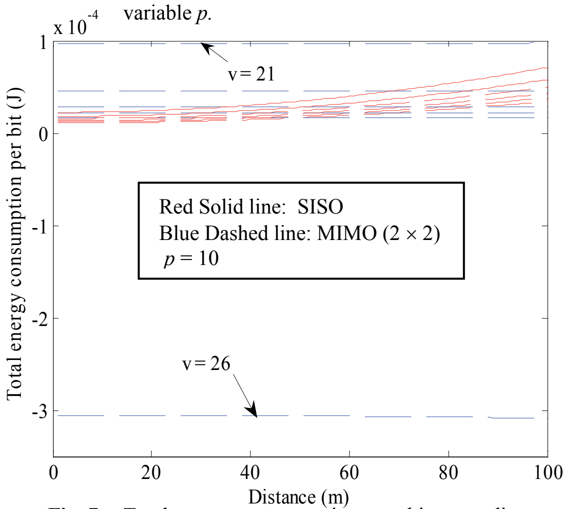

Fig. 7. Total energy consumption per bit over distance for variable v.

Inspired by the set of pair of critical value, we tried to find the relationship between p and v. By using the previously described equations, we obtained the relationship between the boundary value of p and boundary value of v using computer simulations. The relationship is shown in Fig. 8 which is an inverse relationship between them.

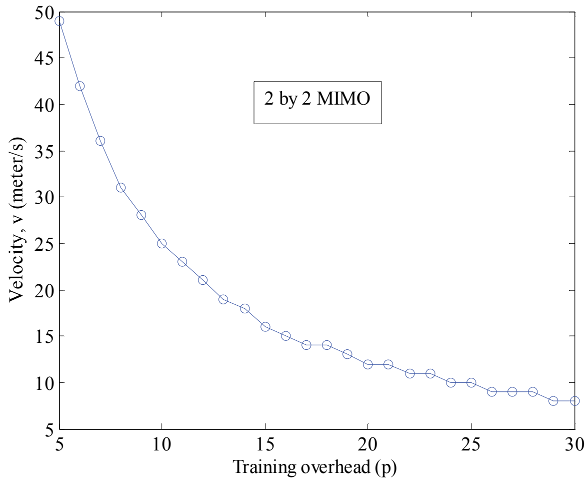

Fig. 8. Boundary value of Velocity over boundary value of training overhead.

3.2 Analytical Approach:

Now we concentrate on deriving a mathematical relation between p and v. We know that R_b^{eff} and R_b are related by the following relation

$$\begin{aligned} R_b^{eff} &= \frac{F - pN_T}{F} R_b \\ &= \frac{\lfloor T_C R_S \rfloor - pN_T}{\lfloor T_C R_S \rfloor} R_b \\ &= \frac{\left\lfloor \frac{3}{4 f_m \sqrt{\pi}} R_S \right\rfloor - pN_T}{\left\lfloor \frac{3}{4 f_m \sqrt{\pi}} R_S \right\rfloor} R_b \\ &= \frac{\left\lfloor \frac{3\lambda}{4v\sqrt{\pi}} R_S \right\rfloor - pN_T}{\left\lfloor \frac{3\lambda}{4v\sqrt{\pi}} R_S \right\rfloor} R_b \end{aligned} \tag{10}$$

Equation (10) can be rewritten as the followings

$$\frac{R_b^{eff}}{R_b} = 1 - \frac{pN_T}{\left\lfloor \frac{3\lambda}{4v\sqrt{\pi}} R_S \right\rfloor} \quad \text{or} \quad \frac{pN_T}{\left\lfloor \frac{3\lambda}{4v\sqrt{\pi}} R_S \right\rfloor} = 1 - \frac{R_b^{eff}}{R_b}.$$

From the above equation, we can find out the relation between p and v using the following equation

$$p = \frac{\left\lfloor \frac{3\lambda}{4v\sqrt{\pi}} R_S \right\rfloor \left(1 - \frac{R_b^{eff}}{R_b}\right)}{N_T}.$$

This equation is not a close form equation as R_b^{eff} is a function of p and v. To solve this equation we use numerical search and found out that the relation between p and v follow the same relation as shown in Fig. 8.

4. Effects of Different Parameters and Discussion

The relation between boundary value of velocity and boundary value of training overhead is influenced by several parameters. These are explored in the following subsections.

4.1 Effect of Number of Transmit and Receive Antennas

The relation between p and v is strongly dependent on the number of transmit and receive antennas and is shown in Fig. 9. From the simulation result it is evident for a fixed value of training overhead, the boundary value of velocity decreases with the increase in number of transmit and receive antennas. Therefore, it can be concluded that the MIMO application reduces the boundary value of the velocity.

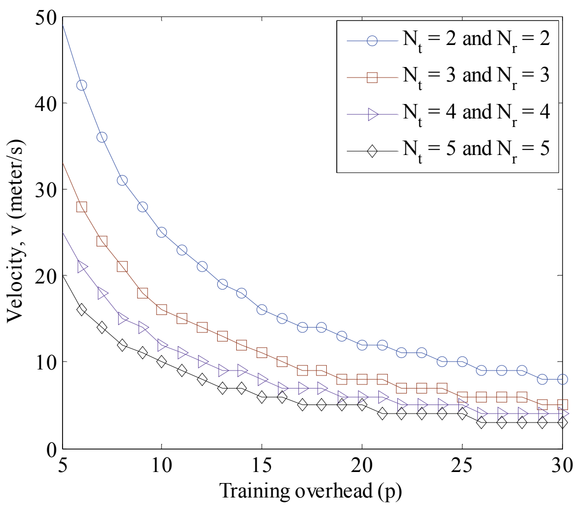

Fig. 9. Boundary value of velocity over boundary value of training overhead for different combination of transmit and receive antenna [where f_C = 2.5 GHz, R_S = 10 kHz]

4.2 Effect of Carrier Frequency

Carrier frequency is the frequency of harmonic waves that are modulated by signals in order to transmit information. A wave at the carrier frequency is sometimes called a carrier wave, or a carrier. The frequency of this carrier has a direct impact on the relation between the boundary values of velocity over boundary values of training overhead. The simulation result is shown in Fig. 10. It shows that the increase in carrier frequency decreases the boundary value of velocity and training overhead for a fixed value of training overhead and velocity respectively. For an example, for $p = 10$, the value of $v = 25$ meter/s for a carrier frequency of $f_C = 2.5$ GHz. The velocity values are $v = 13$, $v = 9$ and $v = 7$ meter/s for the carrier frequencies 5 GHz, 7.5 GHz and 10 GHz respectively.

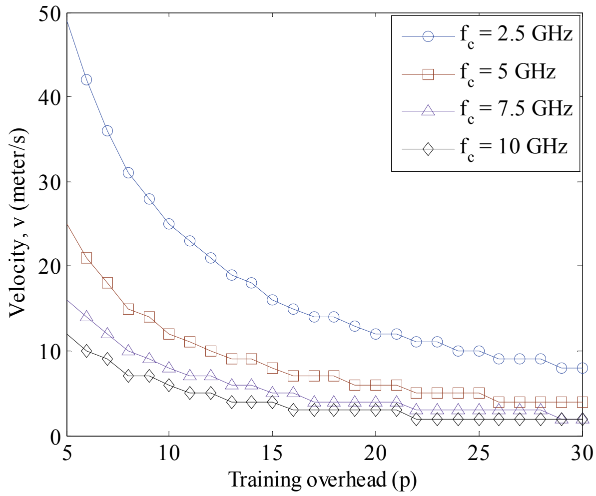

Fig. 10. Boundary value of velocity over boundary value of training overhead for different carrier frequencies [where $N_t = 2$, $N_r = 2$, and R_S = 10 kHz].

4.3 Effect of Symbol Rate

Symbol rate R_S is also an important parameter which has a direct relation with p and v. The simulation result in Fig. 11 shows that the increase in R_S increases the boundary values of p or v while the other is kept constant.

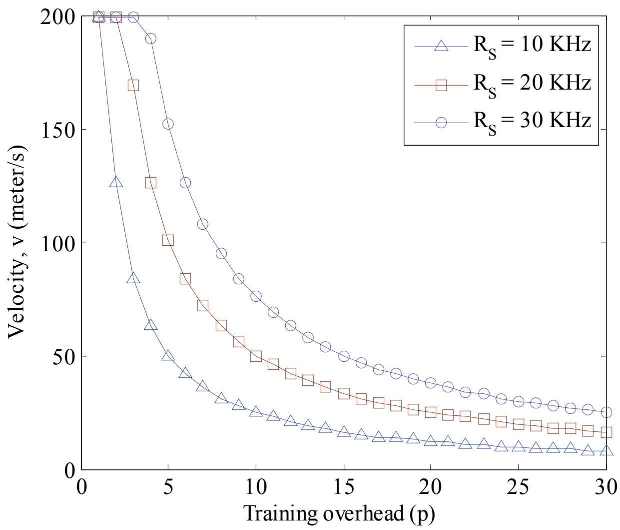

Fig. 11. Boundary value of velocity over boundary value of training overhead for different symbol rate [where $N_t = 2$, $N_r = 2$, and f_C = 2.5 GHz].

4.4 Effect of Modulation Order and Targeted BER

We have simulated the program for different values of modulation order. We also varied the targeted bit error rate (BER) at the receiving side to observe the impact. The result shows that there are no influences of modulation order and targeted BER on the boundary value of velocity and training overhead.

5. Conclusion

We have investigated the velocity of DGN and critical value of training overhead of virtual MIMO-based techniques in cooperative wireless sensor networks. We have provided analytical methods to analyze for both MIMO and SISO based sensor networks. Results show that a set of critical value of velocity and training overhead pair is present for the cooperative communication from a cluster to data gathering node. A graphical relationship is shown between the critical value of training overhead and the boundary value of velocity of DGN beyond which the scheme will not be feasible. The analysis is shown in this paper for a MIMO based cooperative communication for energy-limited wireless sensor networks. A mathematical relation is shown between training overhead and velocity which is solved using numerical analysis. Some parameters are explored which can influence the boundary value of p and v. The results shown here can be validated using experimental tests which remain our future work. It is proposed that the training overhead should be carefully chosen depending on the specific application where the DGN is mobile.

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